WIMP Dark Matter Inflation with Observable Gravity Waves

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We present a successful inflation model based on $\lambda\phi^4$ potential in which a Standard Model (SM) singlet inflaton ϕ, with mass of around a TeV or less, also plays the role of a weakly interacting scalar dark matter particle (WIMP). The WIMP relic abundance generated after inflation is in accord with the current observations. The spectral index n_s lies within the WMAP 1-σ bounds, while the Planck satellite may observe the tensor-to-scalar ratio, a canonical measure of gravity waves, which we estimate lies between 0.003 and 0.007. An unbroken Z_2 parity ensures that the scalar WIMP is absolutely stable.

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The idea that the inflaton, a particle responsible for primordial inflation, also may play the role of scalar WIMP dark matter is most intriguing [1] and therefore worth pursuing. Ref. [2] attempted to implement this idea in chaotic inflation with $m^2\phi^2$ potential. However, a satisfactory scenario could not be realized which is, to a large extent, related to the fact that $m \simeq 10^{13}$ GeV, as demanded by inflation, far exceeds the canonical WIMP mass of a TeV or so. Simply replacing the quadratic potential with a quartic one does not help solve the conundrum for in this case the scalar spectral index n_s and tensor-to-scalar ratio r lie outside the WMAP 2-σ bounds [3].

In a recent paper, hereafter called [4], it was shown that $\lambda\phi^4$ inflation, if supplemented by the non-minimal gravitational coupling $\xi\mathcal{R}\phi^2$ between the SM gauge singlet scalar field ϕ and the curvature scalar $\mathcal{R}$, yields values of n_s (scalar spectral index) and r (tensor-to-scalar ratio) that are compatible with the WMAP 1-σ bounds [3]. This is to be contrasted with minimal $\lambda\phi^4$ inflation whose predictions for n_s and r lie outside the WMAP 2-σ bounds. A series of earlier papers [5]-[11] have previously raised the possibility that the inflaton field ϕ could be identified with the SM Higgs doublet H, provided the non-minimal coupling $\xi = \mathcal{O}(10^3)-\mathcal{O}(10^4)$. While intriguing, doubt about the viability of this identification have been raised in [12] [13]. It stems from the observation that for $\xi \gg 1$, the energy scale $\lambda^{1/4}m_P/\sqrt{\xi}$ of inflation exceeds the effective ultraviolet cutoff scale m_P/ξ, with m_P being the reduced Planck scale, assuming the SM Higgs quartic coupling λ is of order unity. In [4] we easily evade this problem by making ϕ a SM gauge singlet field so that the parameter λ is not all that strongly constrained. Indeed, one finds that consistent with the WMAP 1-σ bounds on n_s and r, λ and ξ can lie within the relatively wide range, $10^{-12} \lesssim \lambda \lesssim 10^{-4}$, and $10^{-3} \lesssim \xi \lesssim 10^2$.

In a separate development, it has been noted by several authors [14] that a stable SM singlet scalar particle, with mass $\sim m_h/2 - 1$ TeV, is a viable cold dark matter candidate (WIMP), provided it has suitable interactions with the SM Higgs doublet H and possibly additional fields. The interaction term $g^2\phi^2|H|^2$ plays an especially important role in these considerations. Recent estimates suggest [15] that with $g^2 \simeq 0.1$ and dark matter mass ~ 1 TeV, the relic WIMP abundance is compatible with the value $\Omega_{\rm CDM}h^2 = 0.1131 \pm 0.0034$ determined by WMAP [3]. This parameter region will be further explored in the ongoing and planned direct detection experiments of dark matter particle.

In this letter we propose a successful and relatively simple scenario of WIMP dark matter inflation by merging together ideas from [4] and [15]. Following [4], we employ non-minimal quartic inflation in which a gravitational coupling of the inflaton to the curvature scalar is included. The model has a further restriction arising from the relic dark matter abundance. It is shown in [15] that for TeV mass WIMP dark matter, the coupling strength g^2 must be of order 0.1 or so. In our case this means that due to radiative corrections involving g^2, the 'effective' quartic coupling is of order 10^{-3}. An important consequence of this WIMP driven inflation model is that it predicts both n_s and r in a fairly narrow range. In particular, r values close to 0.007 may be accessible to Planck satellite searches. Another important feature of our model is the appearance of thermal dark matter relic abundance which arises during preheating and subsequent transition to a radiation dominated universe with temperature close to 10^7 GeV. The energy in the oscillating inflaton field is by then essentially negligible.

Consider the following tree level action in the Jordan frame:

$$S_J^{tree} = \int d^4x\sqrt{-g}\left[-\left(\frac{m_P^2+\xi\phi^2}{2}\right)\mathcal{R} + \frac{1}{2}(\partial_\mu\phi)^2 - \left(\frac{m_\phi^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4\right) - \frac{g^2}{2}\phi^2|H|^2\right], \quad (1)$$

where $m_P = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. Here we have introduced a Z_2 parity under which ϕ is odd, while the SM fields are all even. Hence the scalar ϕ is stable and will play the role of both inflaton and dark matter particle.

First we consider the non-minimal $\lambda\phi^4$ inflation in this model [4]. During inflation, with field values close to m_P, $\lambda\phi^4$ dominates the scalar potential. The relevant one-loop renormalization group improved effective potential [16] is $V_{\rm eff} = \frac{1}{4}\lambda(t)G(t)^4\phi^4$, where $t = \ln(\phi/m_\phi)$, and $G(t) = \exp(-\int_0^t dt'\gamma(t')/(1+\gamma(t')))$, with $\gamma(t)$ being the anomalous dimension of the inflaton field. We employ a leading-log approximation for the effective potential

$$V_{\rm eff}(\phi) \simeq \frac{1}{4}\left(\lambda_0 + \frac{g^4}{8\pi^2}\ln\left[\frac{\phi}{m_\phi}\right]\right)\phi^4, \quad (2)$$

where $\lambda_0 = \lambda(t=0)$, $\lambda_0 \ll g^2$, and we have taken m_ϕ as the renormalization scale. In the Einstein frame with a canonical gravity sector, the kinetic energy of ϕ can be made canonical by defining a new field σ [7],

$$\left(\frac{d\sigma}{d\phi}\right)^{-2} = \frac{\left(1+\frac{\xi\phi^2}{m_P^2}\right)^2}{1+(6\xi+1)\frac{\xi\phi^2}{m_P^2}}. \tag{3}$$

The effective potential in the Einstein frame is then given by

$$V_E(\phi) = \frac{V_{\rm eff}(\phi)}{\left(1+\frac{\xi\,\phi^2}{m_P^2}\right)^2}. \tag{4}$$

The inflationary slow-roll parameters are given by

$$\begin{aligned}
\epsilon(\phi) &= \frac{1}{2}m_P^2\left(\frac{V_E'}{V_E\sigma'}\right)^2, \\
\eta(\phi) &= m_P^2\left[\frac{V_E''}{V_E(\sigma')^2}-\frac{V_E'\sigma''}{V_E(\sigma')^3}\right], \\
\zeta^2(\phi) &= m_P^4\left(\frac{V_E'}{V_E\sigma'}\right)\left(\frac{V_E'''}{V_E(\sigma')^3}-3\frac{V_E''\sigma''}{V_E(\sigma')^4}\right. \\
&+ \left. 3\frac{V_E'(\sigma'')^2}{V_E(\sigma')^5}-\frac{V_E'\sigma'''}{V_E(\sigma')^4}\right),
\end{aligned} \tag{5}$$

where a prime denotes a derivative with respect to ϕ. The slow-roll approximation is valid as long as the conditions $\epsilon \ll 1$, $|\eta| \ll 1$ and $\zeta^2 \ll 1$ hold. In this case the scalar spectral index n_s, the tensor-to-scalar ratio r, and the running of the spectral index $\alpha = \frac{dn_s}{d\ln k}$ are approximately given by

$$\begin{aligned}
n_s &\simeq 1-6\,\epsilon+2\,\eta, \\
r &\simeq 16\,\epsilon, \\
\alpha &= \frac{dn_s}{d\ln k} \simeq 16\,\epsilon\,\eta - 24\,\epsilon^2 - 2\,\zeta^2.
\end{aligned} \tag{6}$$

The number of e-folds after the comoving scale l has crossed the horizon is given by

$$N_l = \frac{1}{\sqrt{2}\,m_P}\int_{\phi_e}^{\phi_l}\frac{d\phi}{\sqrt{\epsilon(\phi)}}\left(\frac{d\sigma}{d\phi}\right), \tag{7}$$

where ϕ_l is the field value at the comoving scale l, and ϕ_e denotes the value of ϕ at the end of inflation, defined by $\max(\epsilon(\phi_e), |\eta(\phi_e)|, \zeta^2(\phi_e)) = 1$. The amplitude of the curvature perturbation $\Delta_{\mathcal{R}}$ is given by

$$\Delta_{\mathcal{R}}^2 = \left.\frac{V_E}{24\,\pi^2\,m_P^2\,\epsilon}\right|_{k_0}, \tag{8}$$

which should satisfy the WMAP normalization, $\Delta_{\mathcal{R}}^2 = (2.43\pm0.11)\times10^{-9}$ [3], at $k_0 = 0.002\,\mathrm{Mpc}^{-1}$.

Using Eqs. (2)-(8) we can obtain various predictions of the radiatively corrected non-minimal $\lambda\phi^4$ inflation model. Once we fix the parameters ξ and the number of e-foldings N_0, we can predict n_s, r, and $\alpha = \frac{dn_s}{d\ln k}$. Note that with $m_\phi \simeq 1$ TeV, the coupling $g^2 \simeq 0.1$ in order for the relic density of dark matter to be compatible with the WMAP observations [15]. In our analysis, we set $g^2 = 0.1$ and $m_\phi = 1$ TeV as reference values. If $\lambda_0 \lesssim g^4/(8\pi^2)$, the potential during inflation is dominated by the radiatively corrected part. We impose $\lambda_0 \geq 0$ for an unbroken Z_2 parity.

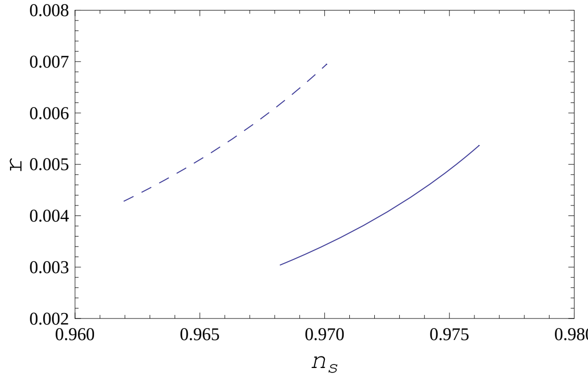

FIG. 1: r vs. n_s with $N_0 = 60$ (solid curve) and $N_0 = 50$ (dashed curve) e-foldings. Both curves lie within the WMAP 1-σ (68% confidence level) bounds.

The predicted values of n_s and r are shown in Figure 1 for the number of e-foldings $N_0 = 60$ (solid curve) and $N_0 = 50$ (dashed curve). In non-minimal $\lambda\phi^4$ inflation [4], the (effective) scalar quartic coupling becomes larger according to ξ values, and n_s and r approach their asymptotic values, $n_s \simeq 0.968$ and $r \simeq 0.0030$ for $N_0 = 60$ and $n_s \simeq 0.962$ and $r \simeq 0.0042$ for $N_0 = 50$. These values correspond to the left edge of each curve in Figure 1. In the present case, for $\lambda_0 \lesssim g^4/(8\pi^2)$, the radiatively induced term in the effective potential dominates the scalar potential and thus the effective quartic coupling has a minimum value. In the limit $\lambda_0 = 0$, n_s and r approach $n_s \simeq 0.976$ and $r \simeq 0.0054$ for $N_0 = 60$ ($n_s \simeq 0.970$ and $r \simeq 0.0069$ for $N_0 = 50$), which correspond to the right edge of each curve in Figure 1. We find that the running of the spectral index $\alpha = \frac{dn_s}{d\ln k}$ very weakly depends on n_s, and $\alpha \simeq -0.0005\,(-0.00075)$ for $N_0 = 60\,(N_0 = 50)$. In Figure 2, we show the ratio of the inflation energy scale ($V^{1/4}$) to the effective ultraviolet cutoff scale ($\Lambda = m_P/\xi$). This ratio becomes larger as ξ is raised. The minimum value for this ratio, $V^{1/4}/\Lambda \simeq 8.7$, is achieved for $\lambda_0 \lesssim g^4/(8\pi^2)$ with $\xi \simeq 2000$. This value marginally exceeds the proposed naturalness bound $V^{1/4}/\Lambda < \mathcal{O}(1)$ [13]. As a more conservative bound, we examine the constraint on the ratio of the Hubble parameter and the effective cutoff scale from the validity of the classical inflationary treatments [12], namely, $\sqrt{\lambda} \ll H/\Lambda \ll 1$. Since $H/\Lambda \simeq (V^{1/4}/\Lambda)^2(\Lambda/m_P)$, we find the ratio $\simeq (8.7)^2/2000 \simeq 0.04$ for $\xi \simeq 2000$, while $\sqrt{\lambda} \simeq \sqrt{g^4/(8\pi^2)} \simeq 0.01$. Thus, this bound is satisfied.

After inflation, the inflaton field starts to oscillate around its potential minimum. During this period the energy density of the inflaton is transmitted to other relativistic fields. Since a single inflaton cannot decay into other particles because of Z_2

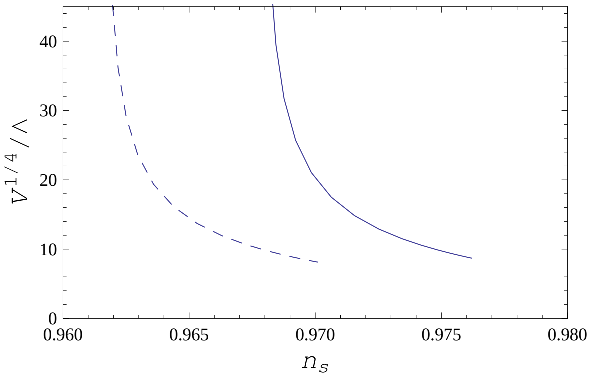

FIG. 2: $V^{1/4}/\Lambda$ vs. n_s with $N_0 = 60$ (solid curve) and $N_0 = 50$ (dashed curve) e-foldings.

parity, preheating [1] via, in our case, the coupling $g^2\phi^2|H|^2$ plays the crucial role in energy transmission. In the first stage of preheating, the inflaton energy density is transmitted to ϕ particles by explosive production through parametric resonance effects with $\lambda\phi^4$ potential. The amplitude of the inflaton filed is reducing its amplitude by ϕ particle production and the expansion of the universe. When this becomes smaller than $m_\phi/\sqrt{\lambda}$, the term $m_\phi^2\phi^2$ in the scalar potential dominates and the Higgs doublets are explosively produced by the (broad) parametric resonance through the coupling $g^2\phi^2|H|^2$. This preheating process ends when the amplitude becomes smaller than m_ϕ/g [1].

Since the inflaton is stable, its oscillations continue without further energy transfer after the preheating era. The oscillating mode has the equation of state of dust and so, in principle, it can play the role of dark matter. The present ratio of the average energy density of this oscillation mode to the number density of photons is estimated as [2]

$$\xi_{\rm dm,0} \simeq 0.44 \left(\frac{m_\phi}{m_P}\right)^{1/2} \left(\frac{\phi_*}{m_P}\right)^2 m_P, \tag{9}$$

where ϕ_* is the oscillation amplitude at time t_* when $m_\phi = H_*$, the Hubble parameter. Since $m_\phi > H$ for $t > t_*$, ϕ_* is basically also the amplitude of the oscillating inflaton today. With $\phi_* = m_\phi/g$, we find $\xi_{\rm dm,0} \simeq 1.5 \times 10^{-37} m_P$ for $m_\phi = 1$ TeV and $g^2 = 0.1$. Comparing it to the observed value by WMAP [3], $\xi_{\rm dm,0} \simeq 1.1 \times 10^{-27} m_P$, we conclude that the oscillating mode has a negligible contribution to the energy density of the present universe. It is worth recalling that successful $m_\phi^2\phi^2$ chaotic inflaton requires $m_\phi \simeq 10^{13}$ GeV, and so $g \simeq 10^7$ is needed to realize the observed value of $\xi_{\rm dm,0}$ [2]! In our case, successful inflation is realized by non-minimal $\lambda\phi^4$ inflation and the inflaton mass plays no role during inflation for $m_\phi \ll 10^{13}$ GeV.

We have seen that the energy density in the remnant inflaton oscillations is tiny compared to the observed dark matter relic density. However, the ϕ particle can be a suitable WIMP dark matter candidate if the universe is thermalized with the reheating temperature high enough for the ϕ particle to be in thermal equilibrium. In the preheating scenario, thermalization of the universe takes place through decays and multiple scatterings of particles (SM Higgs doublets in our model), during explosively produced preheating. A reasonable estimate for the reheating temperature is [1]

$$T_R \sim 0.5\sqrt{\Gamma_h m_P}, \tag{10}$$

where Γ_h is the total decay width of the Higgs boson. For a relatively light Higgs boson with mass $m_h = 120$ GeV for example, the dominant decay mode is $h \to b\bar{b}$, so that

$$\Gamma_h \sim \frac{3}{8\pi} \left(\frac{m_b}{v}\right)^2 m_h, \tag{11}$$

where $m_b \simeq 3$ GeV is the appropriate bottom quark mass, and $v = 246$ GeV is the VEV of the SM Higgs doublet. We find $T_R \sim 10^7$ GeV, which is four orders of magnitude larger than $m_\phi(\simeq 1$ TeV). Thus, we expect that the temperature of the universe is high enough for ϕ particles to be in thermal equilibrium, and the standard WIMP dark matter scenario consistent with the WMAP observations can be realized, as shown in recent analysis [15].

In our analysis above, we set $m_\phi = 1$ TeV in order to keep the inflaton mass much larger than the SM Higgs boson mass, $m_\phi \gg m_h$. This parameter choice makes the preheating process as effective as possible. In general, the preheating process can be reasonably efficient even for $m_\phi \sim m_h$ [1]. If the inflaton mass can be lowered close to half of the Higgs boson mass, the magnitude of the coupling g^2 needed to obtain the correct dark matter relic abundance becomes significantly smaller than 0.1 [15]. In this case, the radiative corrections to the potential is negligible and we can easily obtain $V^{1/4}/\Lambda < 1$ for a successful inflation scenario as shown in [4].

In summary, we have shown that the inflaton and WIMP dark matter can indeed be one and the same particle. In the simplest model this is achieved by supplementing the SM with a stable gauge singlet scalar field. The model overcomes serious challenges faced by chaotic $m^2\phi^2$ inflation [2] and, in addition, turns out be quite predictive. Its dark matter properties will be seriously examined by the ongoing direct detection searches [17] [18]. As far as inflation is concerned the predictions for n_s and r lie within the WMAP 1-σ bounds. With an upper bound of around 0.007 on r, the model can be excluded if the Planck satellite observes values that are significantly larger than this.

Finally, one promising extension of our model is to introduce an SU(2) triplet scalar field with unit SM hypercharge. This would nicely incorporate neutrino masses and mixings via the type-II seesaw mechanism [19]. Interestingly, this extension essentially coincides with a model proposed in [20], and it can also account for the anomalous cosmic-ray positron flux reported by the PAMELA satellite experiment [21]. In addition, as analyzed in detail in [22], in the type-II seesaw extension of the SM, the vacuum stability bound on the Higgs

boson mass can be reduced to coincide with the current experimental lower bound of 114.4 GeV [23].

Note Added

Although our approach in unifying the inflaton and dark matter particle is inspired by Refs. [1] [2], by the recent analysis of SM singlet scalar dark matter [15], and by non-minimal $\lambda\phi^4$ inflation [4], the model presented in this letter turns out to be identical to the ones proposed in Refs. [24] and [25]. In [24], a comprehensive study of certain aspects of this model were presented, and where there is overlap with our work, the results appear to be in broad agreement. However, we emphasize that there are several new and important results in this letter. Thus, (1) we have emphasized the WMAP constraints on the coupling g^2, arising from the thermal relic density of dark matter, and evaluated its direct impact on the effective inflaton quartic coupling. As a result, our inflationary scenario predicts both n_s and r in a narrow range. (2) This feature also then plays an important role in discussing the naturalness of the inflationary scenario as shown in Figure 2. (3) We have considered the preheating scenario after inflation, following [1] and [2], which allows the transition to a radiation dominated universe. Furthermore, we have shown that the energy density in the remnant inflaton oscillations, which plays the role of dark matter in the original scenario [2], can be ignored. (4) Considering thermalization of the universe via preheating, we have estimated the reheating temperature and shown that it is high enough for the singlet scalar to be in thermal equilibrium. This is crucial for a successful WIMP dark matter scenario.

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